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Abstract

Soil thermal properties play important roles in dynamic heat and mass transfer processes, and they vary with soil water content (θ) and bulk density (ρ_b). Both θ and ρ_b change with time, particularly in recently tilled soil. However, few studies have addressed the full extent of soil thermal property changes with θ and ρ_b . The objective of this study is to examine how changes in ρ_b with time after tillage impact soil thermal properties (volumetric heat capacity, C_v , thermal diffusivity, k , and thermal conductivity, λ). The study provides thermal property values as functions of θ and ρ_b and of air content (n_{air}) on undisturbed soil cores obtained at selected times following tillage. Heat pulse probe measurements of thermal properties were obtained on each soil core at saturated, partially saturated (θ at pressure head of -50 kPa) and oven-dry conditions. Generally, k and λ increased with increasing ρ_b at the three water conditions. The C_v increased as ρ_b increased in the oven-dry and unsaturated conditions and decreased as ρ_b increased in the saturated condition. For a given θ , a larger ρ_b was associated with larger thermal property values, especially for λ . The figures of C_v , k and λ versus θ and ρ_b , as well as C_v , k and λ versus n_{air} , represented the range of soil conditions following tillage. Trends in the relationships of thermal property values with θ and ρ_b were described by 3-D surfaces, whereas each thermal property had a linear relationship with n_{air} . Clearly, recently tilled soil thermal property values were quite dynamic temporally due to varying θ and ρ_b . The dynamic soil thermal property values should be considered in soil heat and mass transfer models either as 3-D functions of θ and ρ_b or as linear functions of n_{air} .

Keywords

air-filled pore space, bulk density, soil thermal property, soil water content, thermal conductivity, thermal diffusivity, tillage, volumetric heat capacity

Disciplines

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Thermal property values of a central Iowa soil as functions of soil water content and bulk density or of soil air content

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Abstract

Soil thermal properties play important roles in dynamic heat and mass transfer processes, and they vary with soil water content (θ) and bulk density (ρ_b). Both θ and ρ_b change with time, particularly in recently tilled soil. However, few studies have addressed the full extent of soil thermal property changes with θ and ρ_b . The objective of this study is to examine how changes in ρ_b with time after tillage impact soil thermal properties (volumetric heat capacity, C_v , thermal diffusivity, k , and thermal conductivity, λ). The study provides thermal property values as functions of θ and ρ_b and of air content (n_{air}) on undisturbed soil cores obtained at selected times following tillage. Heat pulse probe measurements of thermal properties were obtained on each soil core at saturated, partially saturated (θ at pressure head of -50 kPa) and oven-dry conditions. Generally, k and λ increased with increasing ρ_b at the three water conditions. The C_v increased as ρ_b increased in the oven-dry and unsaturated conditions and decreased as ρ_b increased in the saturated condition. For a given θ , a larger ρ_b was associated with larger thermal property values, especially for λ . The figures of C_v , k and λ versus θ and ρ_b , as well as C_v , k and λ versus n_{air} , represented the range of soil conditions following tillage. Trends in the relationships of thermal property values with θ and ρ_b were described by 3-D surfaces, whereas each thermal property had a linear relationship with n_{air} . Clearly, recently tilled soil thermal property values were quite dynamic temporally due to varying θ and ρ_b . The dynamic soil thermal property values should be considered in soil heat and mass transfer models either as 3-D functions of θ and ρ_b or as linear functions of n_{air} .

Highlights

- Thermal property values for a range of θ and ρ_b were measured on undisturbed soil cores.
- Freshly tilled soil thermal property values were quite dynamic temporally.
- The thermal property values of a tilled soil were described as 3-D surfaces with θ and ρ_b .
- The thermal property values of a tilled soil varied linearly with n_{air} .

KEYWORDS

air-filled pore space, bulk density, soil thermal property, soil water content, thermal conductivity, thermal diffusivity, tillage, volumetric heat capacity

1 | INTRODUCTION

Surface soil impacts mass and energy transfer between land and the atmosphere, and it is complex and dynamic. Soil thermal properties, including volumetric heat capacity (C_v), thermal diffusivity (k) and thermal conductivity (λ), affect heat and mass transfer in soil. The magnitudes of soil thermal properties depend largely on soil texture, mineral composition, water content (θ) and bulk density (ρ_b) (Campbell, 1985; de Vries, 1963). Several models have been developed to estimate soil thermal properties from water content (Chung & Horton, 1987; Tong, Gao, Horton, Li, & Wang, 2016) or from water content, bulk density and texture (Campbell, 1985; Côté & Konrad, 2005; de Vries, 1963; Johansen, 1977; Lu, Lu, Horton, & Ren, 2014; Lu, Ren, Gong, & Horton, 2007; Lukiashchenko & Arkhangelskaya, 2018; Sadeghi, Ghanbarian, & Horton, 2018; Xie, Lu, Ren, & Horton, 2018).

Under field conditions, soil water content changes with time and depth. Soil properties influenced by water content are critical for modelling and interpreting hydrologic processes, and much research in recent years has focused on understanding dynamic soil properties (Kojima, Heitman, Sakai, Kato, & Horton, 2018; Ochsner et al., 2013; Robinson et al., 2008). Soil bulk density is considered to be static in most hydrological studies, but it is, in fact, dynamic. Implications of this assumption may be significant in some cases (Arya & Paris, 1981; Moldrup et al., 2000; Ochsner, Horton, & Ren, 2001a). The bulk density of surface soil has been shown to change through annual cycles of disturbance due to agricultural practices such as tillage (Alletto & Yves, 2009; Liu, Lu, Horton, & Ren, 2014; Logsdon, 2012; Strudley, Green, & Ascough, 2008; Tian, Lu, Ren, Horton, & Heitman, 2018) and freeze–thaw processes (Staricka & Benoit, 1995). The surface soil bulk density and structural arrangement were altered by shrink–swell processes, erosion and deposition episodically with storm events and flooding (Timm et al., 2006). Liu et al. (2014) reported that the ρ_b of a tilled 0–20 cm silt loam field soil layer increased rapidly after tillage from an initial value of 1.00 ± 0.05 (mean \pm one standard deviation) g cm^{-3} to a relatively stable value of $1.33 \pm 0.03 \text{ g cm}^{-3}$ within 40 days. For a sandy loam soil, ρ_b increased from 1.11 ± 0.05 to $1.35 \pm 0.03 \text{ g cm}^{-3}$ within 2 months after tillage. Tian et al. (2018) reported that following tillage of a loamy sand soil the ρ_b of the 0–10 cm soil layer increased by about 35% over 40 days, whereas the ρ_b of the 10–15 cm soil layer remained relatively stable. Generally, ρ_b can affect θ , and θ can affect ρ_b of shrink–swell soils. As soil ρ_b increases, soil porosity reduces, and thus, the saturated θ value also reduces. At a specified matric potential value, a soil with a large ρ_b can have relatively more small pores than a small ρ_b soil, and thus, it has larger θ .

Some previous studies reported that soil thermal properties varied with θ and ρ_b . Van Rooyen and Winterkorn (1959) evaluated λ data measured on chernozem soil, and the results showed that ρ_b increased from 1.1 to 1.5 g cm^{-3} , leading to λ increasing from 0.42 to $0.85 \text{ W m}^{-1} \text{ K}^{-1}$. Van Duin (1963) reported a similar trend, showing that for a sandy soil, when the porosity decreased by 50%, λ increased by 100%. They also showed that when the porosity increased by 50%, k reduced over the entire θ range. Abu-Hamdeh and Reeder (2000) reported that the λ versus ρ_b relationship differed for various θ and soil textures of repacked Jordanian soils, showing that at a given θ , an increase in ρ_b increased λ , and at a given ρ_b , an increase in θ increased λ . Lu et al. (2014) presented $\lambda(\theta, \rho_b)$ graphs for three hypothetical soils depicting how λ can vary with θ and ρ_b . Using repacked soil samples, Lu, Liu, Heitman, Ren, and Horton (2016) reported that λ tended to increase linearly with ρ_b at a fixed θ for a silt loam soil. Several studies have reported that ρ_b can change with time after tillage but few studies reported how thermal properties change with time after tillage. Most reported results were based on repacked soil samples and few studies reported the relationships between soil thermal properties with θ and ρ_b for undisturbed soil cores. Undisturbed soil cores retain the structural integrity of the *in situ* soil, whereas structure is altered and destroyed in repacked soil cores. Soil structures of repacked and undisturbed soil cores differ, resulting in different soil thermal property relationships (Kaune, Türk, & Horn, 1993; Smith, 1942).

Many existing soil heat transfer models assume that soils have static ρ_b values, which implies that temporal changes in thermal property values are due solely to θ variation. Thus, there exists a need to investigate how θ and ρ_b variations following tillage impact soil thermal property values. Tillage can decrease ρ_b , but following tillage ρ_b increases with time due to rainfall and subsequent wetting and drying cycles. Thus, the main hypothesis of this study is that when bulk density changes with time, the thermal property values versus water content relationships will also change with time. Therefore, the soil thermal property values versus water content curves are not expected to be static with time. The objective of this study is to investigate how thermal properties of a tilled soil vary with θ and ρ_b and how thermal properties of a tilled soil vary with soil air content (n_{air}). Air content, determined as the difference between porosity and water content, indirectly reflects the combined effects of water content and bulk density.

2 | MATERIALS AND METHODS

2.1 | Field site and soil measurements

A bare field ($125 \times 125 \text{ m}$) located at the Agronomy and Agricultural Engineering Farm in Boone country, near

Ames, Iowa (41.98 °N, 93.68 °W), was used in this study. The site had a humid continental climate (Köppen climate classification). The long-term average temperatures of January and July were -12.9°C and 28.8°C , respectively, and the average annual rainfall was 974 mm (US climate data). The Nicollet soil series (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) (Andrews & Diderikson, 1981) at the site had a loam texture (31% sand, 43% silt and 26% clay) and an organic matter content of 5.33%. The topography of the site was relatively flat (slope < 2%). The field was tilled with a rototiller to a depth of approximately 25 cm, and the soil surface was levelled on day of year (DOY) 160 (June 9) 2015 to provide an initial soil bulk density of $0.94 \pm 0.04 \text{ g cm}^{-3}$ (collected on June 10, 2015). The field was kept bare by spraying herbicides for weed control. Undisturbed soil cores were collected at selected times after tillage. Rainfall was monitored at a nearby weather station (Iowa Environmental Mesonet, BOOI4). Metal cylinders with 8.0-cm internal diameter (i.d.) and 5.0-cm height were used to sample the 0–5 cm, 5–10 cm and 10–15 cm soil layers, and cylinders with 7.6-cm i.d. and 7.5-cm height were used to sample the 15–22.5 cm soil layer. Four soil core samples were collected from each soil layer on the following DOYs: 161, 169, 181, 190 and 248. Each soil core was weighed, saturated from the bottom with 0.01 M CaCl_2 solution in a vacuum chamber for about 12 hours, and then weighed while saturated. The soil cores were allowed to gravity drain to equilibrium, and then each soil core was transferred into a pressure cell. In the pressure cells the cores were allowed to equilibrate at -50 kPa matric potential until water drainage from the cores ceased. Thus, the unsaturated water content for each soil core corresponded to a pressure head of -50 kPa . The water that drained from each soil core was collected and weighed, and after equilibration at -50 kPa pressure head each soil core was weighed and oven-dried at 105°C for at least 48 hours and weighed. The saturated water content (θ_s) value for each soil core was set as the total porosity value (i.e., $1 - \rho_b/\rho_s$) for the soil core. The soil particle density value, ρ_s , was $2.65 \pm 0.03 \text{ g cm}^{-3}$ as measured by the pycnometer method (Blake & Hartge, 1986).

Thermal property values for each soil core were measured with a KD2 Pro heat-pulse sensor (METER Group, Inc., Pullman, WA, USA) in a temperature-controlled room (22°C). Measurements were made at three soil water content conditions (i.e., saturated, partially saturated (equilibrated at -50 kPa matric potential) and oven-dry) for each soil core. Although there are various sensors available to measure soil thermal property values (Kodešová et al., 2013), we selected the SH-1 sensor (METER Group, Inc., Pullman, WA, USA) because it was

capable of measuring soil volumetric heat capacity, thermal diffusivity and thermal conductivity. The SH-1 sensor connected to the KD2 Pro (METER Group, Inc., Pullman, WA, USA) consisted of two parallel needle probes (1.3-mm i.d. and 3-cm long) separated by 6 mm. One probe contained a heater and the other had a temperature sensor. With the sensor inserted vertically into the centre of a soil core, a short heat pulse was applied to the heater and the resulting temperature values with time at the sensor probe were recorded for 2 minutes. All three soil thermal properties were determined from the temperature response curve by the internal software of KD2 Pro. For each soil core, three measurements were made at the same position with the same sensor, and 15 minutes of equilibration time was allowed between each heat pulse measurement. Ren, Ju, Gong, and Horton (2005) reported that the sampling volume of the heat pulse method was a cylinder with a 1.4 cm radius. Thus, the sampling volume for the KD2 Pro sensor was approximately 18 cm^3 ($= \pi \cdot (1.4 \text{ cm})^2 \cdot 3 \text{ cm}$). The heat pulse sampling volume was smaller than the soil core volume, so θ and ρ_b values represented a larger soil volume than the thermal property values. Kluitenberg, Bristow, and Das (1995) reported heat pulse sensor errors in k and C_v as 0.6 to 1.4% and 0.1 to 0.3%, respectively. The manufacturer indicated that the accuracy of the SH-1 sensor was within $\pm 10\%$ (KD2 Pro Thermal Properties Analyzer Operator's Manual, http://manuals.decagon.com/Manuals/13351_KD2%20Pro_Web.pdf). The SH-1 sensors were calibrated in agar (10 g L^{-1}) and were inserted into the Delrin verification blocks (included with the KD2 Pro system) to maintain the correct sensor spacing when not in use.

When making the saturated soil measurements, the soil cores were placed in water-containing beakers, with the water in the beakers equal to the soil surface level. Thus, the soil cores were fully saturated at the time of the measurements. To prevent evaporative water loss during the partially saturated soil measurements, each soil core was covered after the SH-1 sensor was inserted.

2.2 | Soil thermal property models

The de Vries (1963) model was used to describe the trend of C_v as a function of θ and ρ_b , and the Lu et al. (2014) model was used to describe the trend of λ as a function of θ , ρ_b and soil texture.

Based on the theory of de Vries (1963), C_v was estimated as the weighted sum of each soil constituent (water, air and solids). Assuming that the contribution of air to C_v was negligible, C_v was expressed as the weighted sum of volumetric heat capacity of water and the volumetric heat capacity of soil solids (Campbell, 1985):

$$C_v = c_s \rho_b + C_w \theta, \quad (1)$$

where c_s ($\text{kJ kg}^{-1} \text{K}^{-1}$) was the soil solid specific heat, and C_w ($4.18 \text{ MJ m}^{-3} \text{K}^{-1}$) was the volumetric heat capacity of water. The c_s value was determined to be $0.931 \pm 0.042 \text{ kJ kg}^{-1} \text{K}^{-1}$ by performing KD2 Pro heat pulse measurements on oven-dry soil.

Based on soil water content and thermal conductivity datasets, Lu et al. (2014) presented an empirical model relating λ to θ , ρ_b and soil texture, as follows:

$$\lambda = \lambda_{dry} + \exp(\beta - \theta^{-\alpha}), \theta > 0, \quad (2)$$

where α and β were factors that affected the shape of the $\lambda(\theta)$ curve. They were estimated from soil particle-size information and ρ_b :

$$\begin{cases} \alpha = 0.67f_{cl} + 0.24 \\ \beta = 1.97f_{sa} + 1.87\rho_b - 1.36f_{sa}\rho_b - 0.95 \end{cases} \quad (3)$$

where f_{cl} and f_{sa} were USDA-fractions of clay and sand, respectively. The α parameter mainly impacted the curvature of the relationship (i.e. the slope of the $\lambda(\theta)$ curve), whereas the β parameter influenced the magnitude of λ . Additional details about the model can be found in Lu et al. (2014).

The magnitude of heat transfer in dry soil is related to soil porosity. Lu et al. (2007) developed a linear relationship between dry soil thermal conductivity (λ_{dry}) and soil porosity. Here, θ_s is used to represent total soil porosity:

$$\lambda_{dry} = -0.56\theta_s + 0.51. \quad (4)$$

The trend in soil thermal diffusivity (k) was modelled as the ratio of the Lu et al. (2014) model estimated λ values to the de Vries (1963) model estimated C_v values. In this study, soil water was assumed to have the thermal properties of free water.

Measured thermal property values were also presented as functions of n_{air} . The n_{air} was calculated as $(\theta_s - \theta)$.

2.3 | Differences between model-derived surface trends and measured values

Each 3-D graph of a soil thermal property versus θ and ρ_b ($C_v/k/\lambda$ vs. θ vs. ρ_b) was drawn based on the appropriate soil thermal property model and the measurements. Statistical calculations were used to quantify the differences between the model-derived thermal property surface trends and the measured soil thermal property values as follows:

$$RMSD = \sqrt{\frac{\sum_{i=1}^n (X_m - X)^2}{n}}, \quad (5)$$

$$NRMSD = \sqrt{\frac{\sum_{i=1}^n (X_m - X)^2}{\sum_{i=1}^n X^2}}, \quad (6)$$

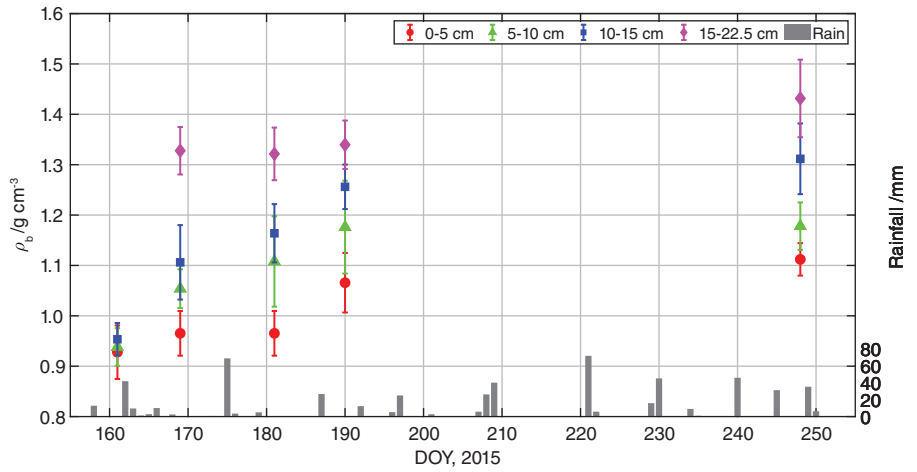
where n was the total number of data points, and X_m and X were the modelled and measured soil thermal property values, respectively. The root mean square deviation (RMSD) and the normalized RMSD (NRMSD) represented the absolute and relative differences, respectively, between the model-derived thermal property surface trends and the measured values.

3 | RESULTS AND DISCUSSION

3.1 | Temporal dynamics of soil bulk density

Figure 1 shows the mean (\pm one standard deviation) ρ_b values for each soil layer and the daily rainfall. During the first 175 mm of rainfall, three wetting and drying cycles occurred at the field site over DOYs 161 to 190 (from June 19 to July 9, 2015). Additional rainfall occurred after DOY 190. The ρ_b values changed with time after tillage, and the values ranged from 0.85 to 1.49 g cm^{-3} during the whole measurement period. The initial (the first sampling time, DOY 161) average ρ_b value was 0.94 g cm^{-3} . Generally, the dynamics of ρ_b could be divided into two stages: a rapid increase stage and a slow increase or relatively stable stage. For the 0–5 cm soil layer, ρ_b increased slightly during DOYs 161 to 190, from 0.93 ± 0.05 to $1.07 \pm 0.06 \text{ g cm}^{-3}$, and then ρ_b tended to be relatively stable. For the 5–10 cm and 10–15 cm soil layers, the rapid increase stage was from DOYs 161 to 190, with ρ_b increasing from 0.94 ± 0.04 to $1.18 \pm 0.09 \text{ g cm}^{-3}$ and from 0.95 ± 0.03 to $1.26 \pm 0.04 \text{ g cm}^{-3}$, respectively, after which ρ_b increased slowly. For the 15–22.5 cm soil layer, ρ_b increased from 1.33 ± 0.05 to $1.43 \pm 0.08 \text{ g cm}^{-3}$. The goal of this study was not to explore the precise functional relationship of ρ_b with time, but it was to collect soil cores with time after tillage that captured the wide range of ρ_b values in the field after tillage. Alletto and Yves (2009), Liu et al. (2014) and Tian et al. (2018) reported that under conventional tillage, ρ_b of the tilled soil layer increased in the first few weeks after tillage, which was consistent with our findings. Increases in ρ_b after tillage were the combined effects of gravity and the wetting–drying process (Alletto & Yves, 2009).

FIGURE 1 The mean (\pm one standard deviation) bulk density (ρ_b) values for the 0–5 cm, 5–10 cm, 10–15 cm and 15–22.5 cm soil layers and the daily rainfall versus day of year (DOY). The error bars indicate one standard deviation



3.2 | Soil thermal properties varied with bulk density over a range of water contents

The magnitudes of the soil thermal property values differed between loose soil conditions and more compacted soil conditions, because soils under loose and more compacted conditions contained different volume fractions of soil constituents (water, air and solids), which had very different thermal property values. In this paper, the C_v and k are presented first, followed by λ , because λ values are derived from the heat-pulse sensor-determined C_v and k values. Figure 2 shows that k and λ increased with increasing ρ_b at the three water content conditions. In the figure, each point is the average of actual triplicate measurements made on a soil core at a given θ , and the solid lines indicate trends. The mean standard deviations of the triplicate measurements for C_v , k and λ for all of the measurements were $0.022 \text{ MJ m}^{-3} \text{ K}^{-1}$, $0.006 \text{ mm}^2 \text{ s}^{-1}$ and $0.010 \text{ W m}^{-1} \text{ K}^{-1}$, respectively. Generally, the slopes of the thermal property versus ρ_b curves followed the order of partially saturated (water content at -50 kPa matric potential) $>$ saturated $>$ oven-dry (shown in Table 1). The C_v increased as ρ_b increased for the oven-dry and partially saturated conditions, whereas they decreased as ρ_b increased for the saturated soil cores. The reason C_v decreased as ρ_b of the saturated cores increased was that θ_s decreased as ρ_b increased. Because the heat capacity of water was larger than the heat capacity of soil solids, and saturated soil cores with smaller ρ_b contained more water than saturated soil cores with larger ρ_b , the smaller ρ_b cores had larger C_v than the larger ρ_b cores.

For soil cores at a given ρ_b , the larger the θ , the larger the C_v and λ . Differing from C_v and λ , the values of k for cores at the partially saturated condition were larger than those at the saturated condition. This occurred because C_v increased linearly with θ , whereas λ versus θ experienced a relatively large slope at the partially saturated condition, causing the ratio $k = \lambda/C_v$ to reach a maximum value in partially

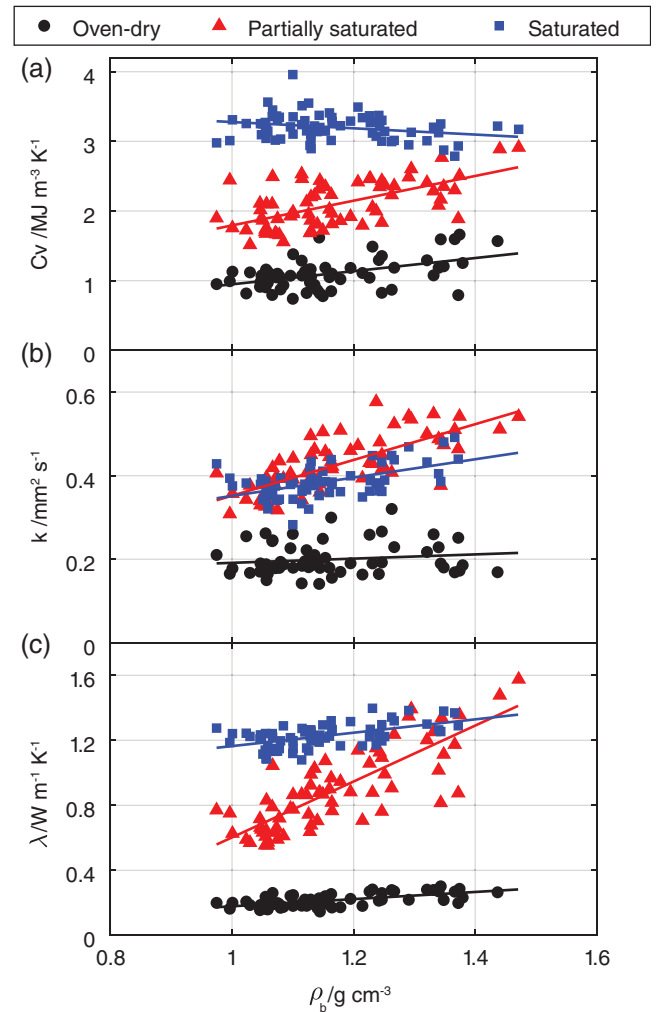


FIGURE 2 Measured soil (a) volumetric heat capacity (C_v), (b) thermal diffusivity (k) and (c) thermal conductivity (λ) versus bulk density (ρ_b) at the oven-dry, partially saturated (water content at -50 kPa matric potential) and saturated conditions. The solid lines indicate trends. The saturated water content values were set equal to the total porosity values

TABLE 1 The linear relationships for soil thermal property values (C_v , k and λ) versus bulk density at the oven-dry, partially saturated (water content at -50 kPa matric potential) and saturated conditions. The intercept (a), slope (b), coefficients of determination (R^2) values and p -values are included

Thermal property	Water content	a	b	R^2	p -value
C_v	Oven-dry	0.004	0.943	0.236	<.05
	Partially saturated	0.002	1.791	0.387	<.05
	Saturated	3.719	-0.441	0.065	<.05
k	Oven-dry	0.141	0.050	0.023	.24
	Partially saturated	-0.067	0.418	0.583	<.05
	Saturated	0.129	0.223	0.297	<.05
λ	Oven-dry	-0.042	0.220	0.412	<.05
	Partially saturated	-1.107	1.709	0.658	<.05
	Saturated	0.740	0.425	0.326	<.05

saturated soil. The ranges of thermal property values measured at the partially saturated condition were larger than those at the oven-dry and saturated conditions, especially for λ . A main reason that the partially saturated soil had the largest ranges in thermal property values was that it had the largest range in θ values. The large θ range at matrix potential of -50 kPa was because the soil samples with a consolidated structure had a larger water-retention capacity (i.e. water content) at this matrix potential than did samples with less consolidated structure.

The regression results of soil thermal property values versus bulk density are shown in Table 1. Even though the coefficients of determination (R^2) were less than 0.65, all of the linear relationships between soil thermal properties and bulk density were significant (p -value <.05) with the exception of k versus ρ_b in the oven-dry condition (p -value = .24). The results indicated that ρ_b impacted soil thermal properties significantly. For C_v versus ρ_b , the slope values (b values in Table 1) varied at the three water content conditions, as partial saturation \approx two times that at oven-dry \approx four times that at saturation. For k versus ρ_b , the slope value at partial saturation \approx two times that at saturation. For λ versus ρ_b , the slope value at partial saturation \approx four times that at saturation \approx eight times that at oven-dry. The various slope values represent the combined effects of the differing thermal property values of the soil components.

3.3 | Soil thermal properties varied with water content at specific bulk density values

Figure 3 has three sections and each section shows how a selected thermal property varies with θ for two soil cores at different ρ_b values. Each point in the figure is the average of triplicate measurements made on a soil core at a given θ . The C_v values tended to increase linearly with θ . For the two ρ_b values, the C_v data groups were almost parallel. As shown in Figure 3b, k increased noticeably with θ at relatively small θ values, and then decreased at large θ values. Figure 3c shows that λ increased sharply with θ at relatively small θ values, and then increased slowly as θ increased. These results were consistent with the trends of thermal property values versus θ reported by others (de Vries, 1963; Lu et al.,

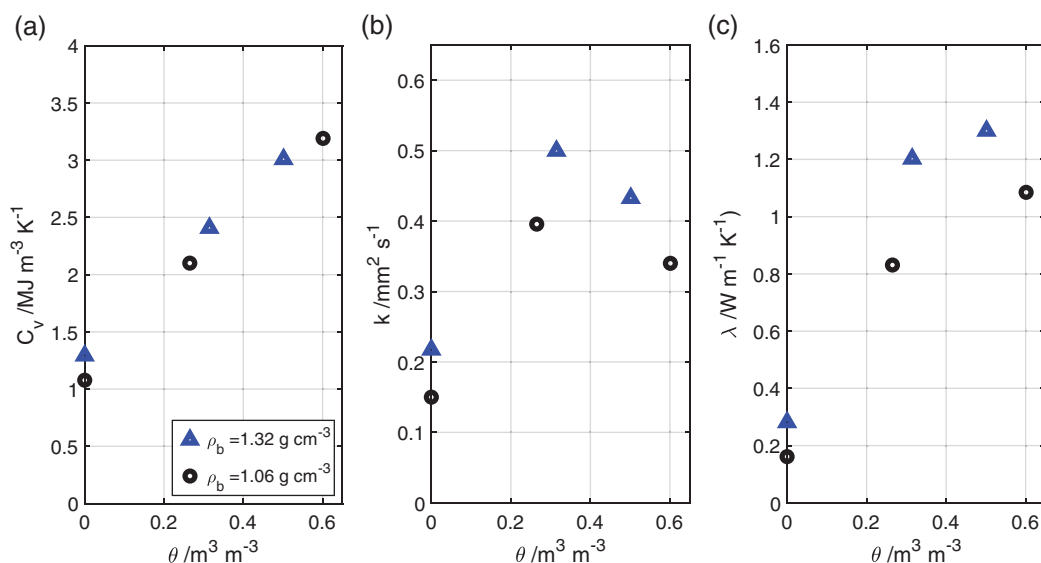


FIGURE 3 Measured soil (a) volumetric heat capacity (C_v), (b) thermal diffusivity (k) and (c) thermal conductivity (λ) versus water content (θ) for two soil cores at different values of bulk density (ρ_b)

2014, 2016; van Duin, 1963; van Rooyen & Winterkorn, 1959). Figure 3 also shows that for a given θ , a larger ρ_b always resulted in larger values for each of the soil thermal properties. The relative effects of bulk density on thermal properties were most pronounced in the oven-dry condition. The oven-dry core with a 25% larger ρ_b had 20, 45 and 74% larger C_v , k and λ values, respectively, than the core with smaller ρ_b . The results indicated that at the oven-dry condition λ was more sensitive to ρ_b than were C_v and k . Heat capacity was larger for water than it was for soil solids, whereas λ was larger for soil solids than it was for water; thus, it was not surprising that the relative effect of ρ_b was the smallest for C_v and the largest for λ . Therefore, λ was the thermal property expected to be most affected by dynamic ρ_b . Higher density ensured better connection between grains. The impacts of ρ_b on soil thermal properties of these undisturbed soil cores were in agreement with the results for repacked soil samples reported by Van Rooyen and Winterkorn (1959), van Duin (1963), Abu-Hamdeh and Reeder (2000) and Lu et al. (2014, 2016).

3.4 | Soil thermal properties varied with water content and bulk density

To clearly show how soil thermal property values varied with θ and ρ_b , the variables were plotted as 3-D graphs (Figure 4). The graphs show how the measured values and the estimated trends derived from the de Vries (1963) and Lu et al. (2014) thermal property models vary with θ and ρ_b . The thermal property models were not fitted to the measured values, but they were used to estimate trends in the measurements. Because data were collected over a range of θ and a range of ρ_b , the data did not graph as curves, but instead they graphed as surfaces. The 3-D graphs represented the variations of soil thermal properties with θ and ρ_b as measured on undisturbed cores collected from the field at various times following tillage.

The de Vries (1963) model was used to describe the trend of C_v . In oven-dry soils, C_v increased gradually as ρ_b increased as only solids contributed to C_v . At the partially saturated condition, both water and solids contributed to C_v ; thus, C_v increased most sharply with increasing θ and increasing ρ_b . For the saturated soil cores, the larger the ρ_b , the smaller the θ_s ; therefore, C_v tended to decrease with increasing ρ_b .

The Lu et al. (2014) model was used to describe the trend in λ . In oven-dry soils, λ increased as ρ_b increased. For the partially saturated condition, λ increased as both ρ_b and θ increased. But unlike C_v , at saturation λ increased as ρ_b increased, even though θ_s decreased as ρ_b increased. Because the λ of water was smaller than the λ of soil solids, when ρ_b increased the fraction of soil solids increased, so λ of the whole soil increased.

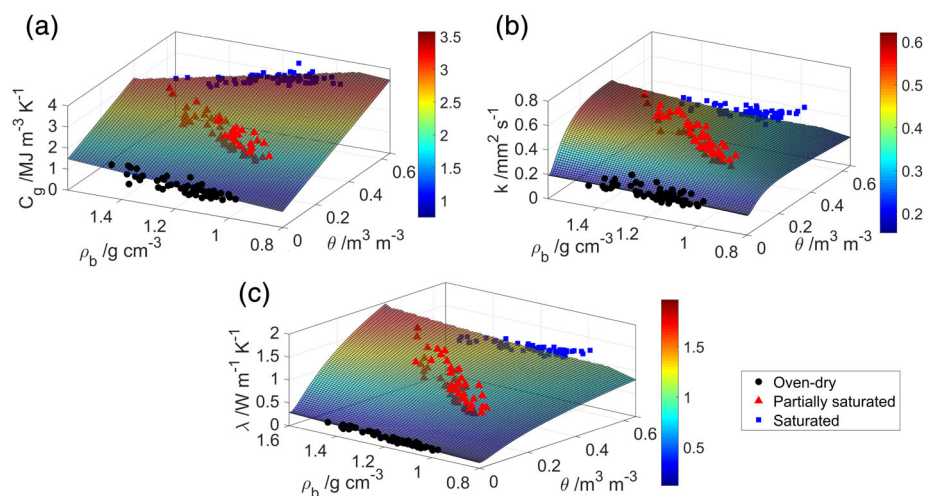
The ratio of the Lu et al. (2014) estimates to the de Vries (1963) estimates was used to derive the trend in k . The k values increased as ρ_b increased for each of the three water-content conditions, and the maximum value of k occurred at the partially saturated condition for each soil core. It was obvious that λ and k varied nonlinearly with θ , whereas they had nearly linear increases with increasing ρ_b .

Figure 4 indicates visually how well the trend curves derived from the soil thermal property models represent the measurements. Generally, the estimated trends well represented the measured soil thermal property values. The average normalized RMSD values were within 0.118, and the correlation coefficients (r) between the measured and model estimated trend soil thermal property values were larger than 0.93 across all of the soil water content conditions (statistical evaluations are shown in Table 2).

3.5 | Soil thermal properties varied linearly with soil air content

Figure 5 displays soil thermal property versus n_{air} linear relationships, and Table 3 provides the linear regression results.

FIGURE 4 Measured soil (a) volumetric heat capacity (C_v), (b) thermal diffusivity (k) and (c) thermal conductivity (λ) versus water content (θ) and bulk density (ρ_b) at the oven-dry, partially saturated (water content at -50 kPa matric potential) and saturated conditions. The surfaces of C_v and λ versus θ and ρ_b were estimated by the de Vries (1963) and Lu et al. (2014) models, respectively, and k values were estimated as the ratio of estimated λ to C_v values



C_v			k			λ		
RMSD /MJ m ⁻³ K ⁻¹	NRMSD	r	RMSD /mm ² s ⁻¹	NRMSD	r	RMSD /W m ⁻¹ K ⁻¹	NRMSD	r
0.259	0.099	0.97	0.045	0.118	0.93	0.108	0.111	0.97

TABLE 2 The root mean square deviation (RMSD) and normalized RMSD (NRMSD) values for the soil thermal properties, and correlation coefficient (r) between measured and modelled soil thermal properties for all of the measured soil water contents

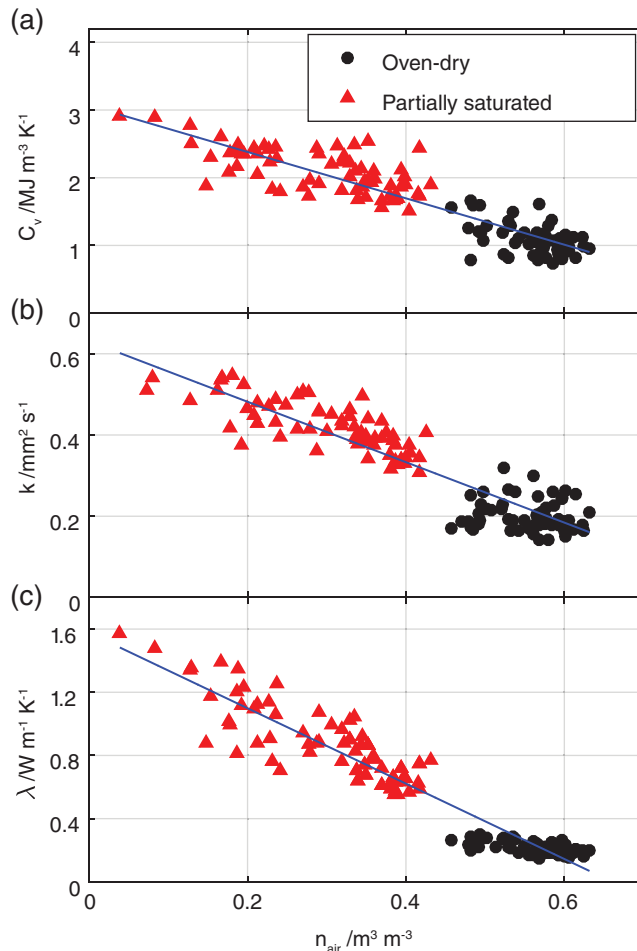


FIGURE 5 Measured soil (a) volumetric heat capacity (C_v), (b) thermal diffusivity (k) and (c) thermal conductivity (λ) versus air content (n_{air}) at the oven-dry and partially saturated (water content at -50 kPa matric potential) conditions. The solid lines were fitted to the measured values

The soil thermal property values linearly decreased as n_{air} increased, and all of the linear relationships were significant (p -value $< .01$), with R^2 values of 0.84, 0.86 and 0.91 for C_v , k and λ , respectively. The λ and n_{air} relationship was the strongest, which was reasonable because the λ value of air (0.025 W m⁻¹ K⁻¹) was about one order of magnitude less than the λ value of water (0.596 W m⁻¹ K⁻¹) and about two orders of magnitude less than the λ value of soil minerals (2.5 W m⁻¹ K⁻¹) (Campbell & Norman, 1998; table 8.2). These linear thermal property trends with air content were

TABLE 3 The linear relationships for soil thermal properties (C_v , k and λ) versus air content at the oven-dry and partially saturated (water content at -50 kPa matric potential) conditions. The intercept (a), slope (b), coefficients of determination (R^2) values and p -values are included

Thermal property	a	b	R^2	p -value
C_v	3.065	-3.424	0.835	$< .01$
k	0.631	-0.744	0.856	$< .01$
λ	1.576	-2.386	0.915	$< .01$

similar to those of Ochsner, Horton, and Ren (2001b), who reported linear trends for repacked soil cores representing four soils over ranges of water content and bulk density. Because undisturbed soil cores are better representatives of field soil structure than are disturbed packed soil samples, it is an important discovery to learn that, similar to disturbed soil samples, undisturbed soil cores also have linear relationships with n_{air} .

The R^2 values of the regression equations for soil thermal property values versus air content (Table 3) were much larger than those for soil thermal property values versus bulk density (Table 1). Soil thermal property values vary with both θ and ρ_b ; thus, it is less than satisfactory to describe soil thermal properties using only θ or ρ_b . Air content, the third phase component of soil, reflects a combination of information on water content and bulk density. Thus, air content is a viable alternative to water content and bulk density for relating to soil thermal property values.

This is the first study to report linear relationships between thermal property values and air content for undisturbed soil. This discovery indicates that there is a possibility to use simple linear relationships to describe thermal properties in field soils experiencing dynamic water content and bulk density. In the field, water content and bulk density, and thus air content, can be determined with the thermo-TDR sensor (Liu et al., 2014; Lu et al., 2016; Lu, Horton, & Ren, 2018; Ochsner et al., 2001a, 2001b; Ren, Ochsner, & Horton, 2003; Tian et al., 2018). Future research can focus on determining *in situ* soil property relationships for fields that experience transient water content and bulk density.

4 | CONCLUSIONS

Undisturbed soil cores were collected at a field site following tillage and subsequent rainfalls. The thermal

properties of soil cores were measured as functions of θ and ρ_b and as functions of n_{air} at saturated, partially saturated (water content at -50 kPa matric potential) and oven-dry conditions.

The results indicated that the ρ_b of a recently tilled field soil did not remain constant but increased during subsequent wetting and drying cycles. Soil thermal properties were not only affected by θ , but also by dynamic ρ_b . Properties k and λ increased with increasing ρ_b , and the slopes of the relationships followed the order of partially saturated > saturated > oven-dry. Property C_v increased as ρ_b increased in oven-dry and partially saturated soils, whereas it decreased with increasing ρ_b in saturated soils. For a given θ , larger ρ_b was associated with larger thermal property values, especially for λ values. Surface trends displayed in 3-D figures, derived from the Lu et al. (2014) and de Vries (1963) models, described the measured thermal property values well with NRMSD values within 0.118. It was a new discovery that undisturbed soil thermal property values and soil air content had simple linear relationships. These results improved our understanding of the relationships between soil thermal property values with θ and ρ_b and with n_{air} of a recently tilled field soil, and they indicated that dynamic ρ_b should be included in soil heat and mass transfer models, especially for tilled soil conditions. The impact of dynamic bulk density on soil water content, temperature and soil heat and mass transfer processes should be explored further in future investigations.

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DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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